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THESIS

**THE MODIFICATION OF A SURFACE SHIPBORNE
RADAR (DECCA 1226) IN ORDER TO MEET
MILITARY STANDARDS (HIGH RESOLUTION)
WITHOUT CHANGING ITS ELECTRONIC
SIGNATURE**

by

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March 1996

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WITHOUT CHANGING ITS ELECTRONIC SIGNATURE**

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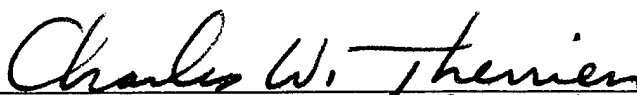
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ABSTRACT

This is a theoretical study examining the possibility to use a commercial, shipborne navigational radar, for target classification and identification, without changing its electronic signature. The reason for such a modification is that using sophisticated pulse forms for target recognition can betray the user's presence and give an intelligence advantage to potential enemy platforms.

In order to extract a target's class or identity, the data of the radar's video detector are fed to a high performance PC with digitizing capability. There the target's class is obtained through a series of transforms, while the target's identity is obtained by computing the target's frequency response to a very short pulse using the MUSIC method. While the classification process does not require any changes in the transmitter, in order to obtain target identification in tactically useful ranges it is necessary to increase the transmitter's power and add an additional very short pulse.

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I. INTRODUCTION

The rapid advance of military technology has provided naval forces with sophisticated radars capable of detecting and identifying surface or air targets from large distances. On the other hand the sophistication of the radars is detectable in the transmitted pulse and often characterizes and identifies the platform which carries it. The electronic equipment used to extract the identity of a platform from its emissions are called ESM (Electronic Support Measures) and their advance has reached the point where it is often possible for an enemy to identify a ship by name (e.g. USS LEYTE GULF) thus gaining an Intelligence advantage. An additional disadvantage of a unique transmission is that it can be used by the opponent's anti-radiation missiles (also known as Homing Anti-Radiation Missiles (HARM)). These missiles can be programmed to identify a characteristic radar transmission and attack the platform that carries it the same way one could locate and attack an enemy in the dark, by spotting his searchlight and then shooting at the direction of the light beam. Many times the tactical situation dictates a specific style of naval warfare that resembles a hide and seek game. In such cases the naval units are not allowed to use their radars freely, thereby giving away their presence. Most of the time they are obliged to radiate only in their less sophisticated navigational radars in order to "hide" in the returns of standard merchant ships. These radars are usually commercial units and are identical with the ones used by the merchant Navy. In such a case a military ship is deprived of all of the "professional extras" his military radar might provide in order to conceal its identity for a desired period of time. The fact that a naval unit is operating at a fraction of its detection potential does not relieve its personnel from the burden of having a clear and accurate picture of the area around it. It simply makes this burden heavier.

The idea that motivated this thesis was the attempt to convert a commercial radar in such a way as to provide a higher level of target identification, using high resolution techniques, without at the same time changing the radar's usual electronic signature. If one could achieve this, a ship could execute its military mission while retaining a level of

anonymity that would protect it from being identified or possibly assaulted. A recent example of the complexity of modern naval warfare is the crisis in the Persian Gulf. In this theater of operations naval units had to ensure the safe passage of commercial ships by patrolling areas close to hostile shores where anti-ship missiles could be based.

The nature of this mission gave an advantage to the enemy who was operating from concealed positions and did not have any ambiguities about the identity of its target. The above introduction does not imply that the only means to identify an enemy is a high resolution radar. There is a plethora of electrooptic devices that can also serve this purpose. Nevertheless a correct tactical picture is never based on one sensor only; it is formulated by a variety of them, and a good low cost navigational radar that not only can hide the electronic presence of a military naval vessel, but can also provide good target vessel identification, would prove extremely valuable. A radar very common both in the merchant Marines and the Navies of many countries is the DECCA 1226. The use of the radar in a variety of platforms makes it a perfect candidate for a modification that would add a target classification/identification mode, to be used in situations that dictate covert naval operations. The particular radar is not the only one that could be modified for operations of such nature. The element that restricted the choice in DECCA, is that Hellenic Navy ships carry DECCA radars for their navigation, thus the interest of the Hellenic Navy is self-evident. That does not mean that the principles developed in this thesis cannot be applied in other radars as well. It will become obvious that the results of this research could be utilized to modify many commercial navigational radars. The only change from case to case would be the hardware modifications required to add the target identification potential to the specific radar.

II. THEORETICAL BACKGROUND

A. DECCA 1226 DESCRIPTION - HIGH RANGE RESOLUTION PULSE REQUIREMENTS

The Decca 1226 or AC 1226 is a true motion non-coherent navigational radar using a magnetron to generate its output pulse. This type of radar is carried onboard a large number of merchant and war ships. Furthermore its transmission characteristics are similar to other radars of the same manufacturer [4], a fact that makes it difficult for an ESM system to identify a platform just by the interception of a Decca 1226 transmission. The main characteristics of the radar are shown in Table 2.1 while the available range

TRANSMITTER	TYPE 65160
Frequency Band	9380 - 9440 Mhz
Magnetron Peak Power	25 KW
Pulse Length	50 - 250 - 1000 ns
PRF (pulses per second)	3300 - 1650 - 825
Magnetron Mean Power	4 - 10 - 21 Watts
Frequency Modulation	50 hz
Interpulse Period Variation	+ 7.5 Or - 7.5 μ s
RECEIVER	TYPE 65160
I.F. Amplifier	Logarithmic
Intermediate Frequency	60 Mhz(nominal)
Bandwidth (short pulse)	18 Mhz
Bandwidth (medium & long pulse)	5 Mhz

Table 2.1. Characteristics of the AC 1226 transmitter and receiver units.

scales and their corresponding pulse lengths are shown in Table 2.2.

RANGE SCALE		PULSE LENGTH (ns)	
Nautical miles	Kilometers	Short	Long
0.25	0.5	50	50
0.5	1	50	250
0.75	1.6	50	250
1.5	2	50	250
3	3.2	250	1,000
6	4	250	1,000
12	22	250	1,000
24	44	1,000	1,000
48	89	1,000	1,000

Table 2.2. Range scales and their corresponding pulse lengths for the AC 1226.

The shortest pulse the AC 1226 can provide is that of 50 ns, which corresponds to range scales of 1.5 nm and less. According to reference [1], the equation relating the required pulse length Δt to resolve two targets separated by ΔR is:

$$\Delta R = \frac{c \times \Delta t}{2} \quad (2.1)$$

(were $c = 3 \times 10^8$ m/s). Thus with a pulse length of 50 ns we could discriminate point scatterers separated in range by 7.8 m; conversely, if we desire a range resolution of 1 m we need a pulse length of 6.9 ns. In any case, since the short pulse length of 50 ns was designed for short ranges which do not offer any tactical advantage, the DECCA 1226 transmitter must be modified in such a way as to provide the available target resolution of 7.8 m in a longer range. Leaving the pulse duration intact and just increasing the

transmitter's power would provide the radar with a degree of high resolution completely undetectable from almost any ESM system monitoring the transmission of a platform carrying the modified radar. On the other hand a resolution of almost 8 m could provide target recognition for only relatively large vessels, the size of a frigate and larger. This does not cover the case of smaller but equally dangerous platforms carrying anti-ship missiles, such as corvettes and fast patrol boats, a rather anticipated opponent in restricted or coastal waters.

As a result of the above consideration we would like to further modify the transmitter in a way to provide the standard AC 1226 waveforms plus an additional "HRR" mode, yet not betray the "military" character of the radar. To accomplish this the operator could use the target recognition feature only for "suspicious" targets, radiating in the specific mode for a very short time (one pulse burst) and in a specific direction to minimize the chance for enemy ESM to become alerted.

The obligatory DECCA 1226 disguise (no frequency or phase modulation) does not allow us to consider any of the HRR techniques utilizing the properties of phase modulated pulses described in [1]. The only permissible method would be using short duration pulses. In this case, we could modify the transmitter to provide the desired pulse length and peak power. We would then need to modify the receiver to compensate for the increased bandwidth, peak power, and enhance its signal processing capabilities. This enhancement can be achieved [10] by connecting a high performance microcomputer (PC) with a digitizing capability (or a digitizing device connected to a PC) to the video output of the receiver. A rough sketch of the receiver modifications is shown in Figure 2.1 at the following page.

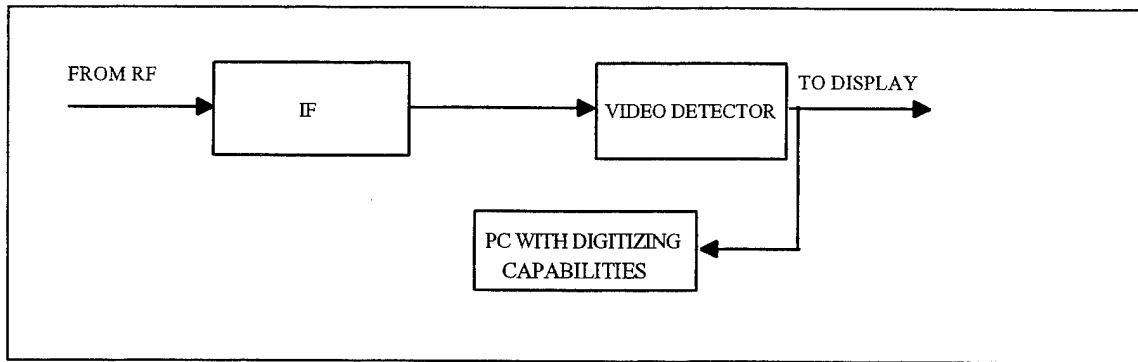


Figure 2.1. Block diagram for the receiver modification.

The connection of the PC with the digitizing capability in the video detector output gives us the opportunity to implement target identification techniques based on narrowband signals [2]. In the chapters to follow we examine the necessary modifications in the radar's transmitter and receiver as well as the processing capabilities added by the use of a high performance PC.

B. TARGET RECOGNITION USING ULTRAWIDEBAND SIGNALS (VERY SHORT PULSE CASE)

According to [11] when a short pulse is transmitted toward a target, the returning echo is the target's impulse response or the target's frequency response if the returned signal is Fourier transformed. The impulse response of an arbitrary target consists of two distinct sets of waveforms. The discontinuities in electrical characteristics at the boundaries of the object cause impulses, while the currents induced on the surface of the object cause reradiation at frequencies which depend on the shape, size, and material of the object. These frequencies are called "natural frequencies." The amplitudes, phases, and times between these components also depend on the aspect angle θ at which the object is observed.

The impulse response $h(t, \theta)$ of an arbitrary target (known as the target signature), is given by

$$h(t, \theta) = \sum_{l=1}^L \alpha_l(\theta) \delta[t - t_l(\theta)] + \sum_{m=1}^M b_m(\theta) \exp \{f_m[t - t_m(\theta)]\} u[t - t_m(\theta)] \quad (2.2)$$

Here, L is the number of impulsive components in the echo, M is the number of natural modes of oscillation in the response, $a_l(\theta)$ and $b_m(\theta)$ are complex amplitudes depending on the l^{th} and m^{th} components of the natural modes, f_m is the m^{th} natural resonant frequency corresponding to the poles in the complex plane, and $u(t)$ is the unit step function.

1. Object Recognition using Target Range Image

A target response in the form of a range image, corresponding to scattering points on the target, is described in [2] for recognition of stationary and moving sonar targets. The transmission is a series of short pulses. Since the radar transmission is also a series of short pulses, the scheme is applicable for radar targets as well. The generalized block diagram of this system is shown in Figure 2.2 . If a target is stationary, the output of the

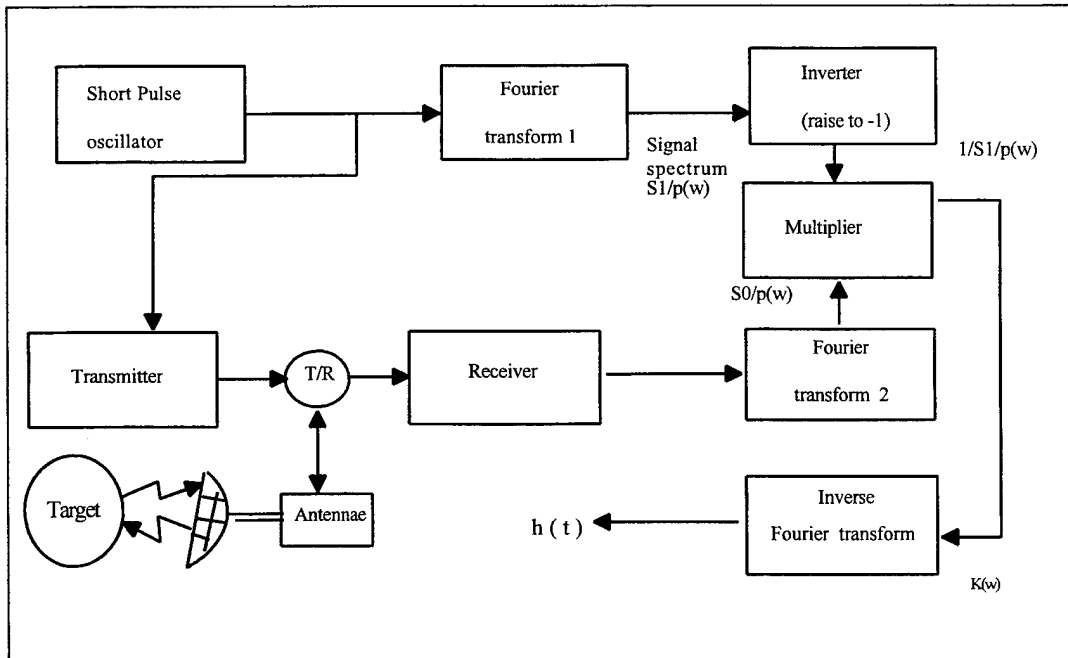


Figure 2.2. Generalized block diagram of signal recognition system. From V.G. Nebadin, "Methods and Techniques of Radar Recognition."

third (inverse) Fourier transform is a signal of the form

$$h(t, \theta) = \sum_{i=1}^P A_i(\theta) \delta(t - t_i) \quad (2.3)$$

where $A_i(\theta)$ are constants proportional to the RCS of scattering points, $\delta(t)$ is the Dirac delta function, and P is the number of scattering points. If the target is moving, the output signal is given by

$$h(t, \theta) = \sum_{i=1}^P A_i(\theta) \delta(t - \frac{t_i}{D}) \quad (2.4)$$

where $D = f_s / f_t$ is a Doppler coefficient, f_s is the transmitted frequency and f_t is the target echo frequency.

The block diagram of a recognition system for moving targets is shown in Figure 2.3.

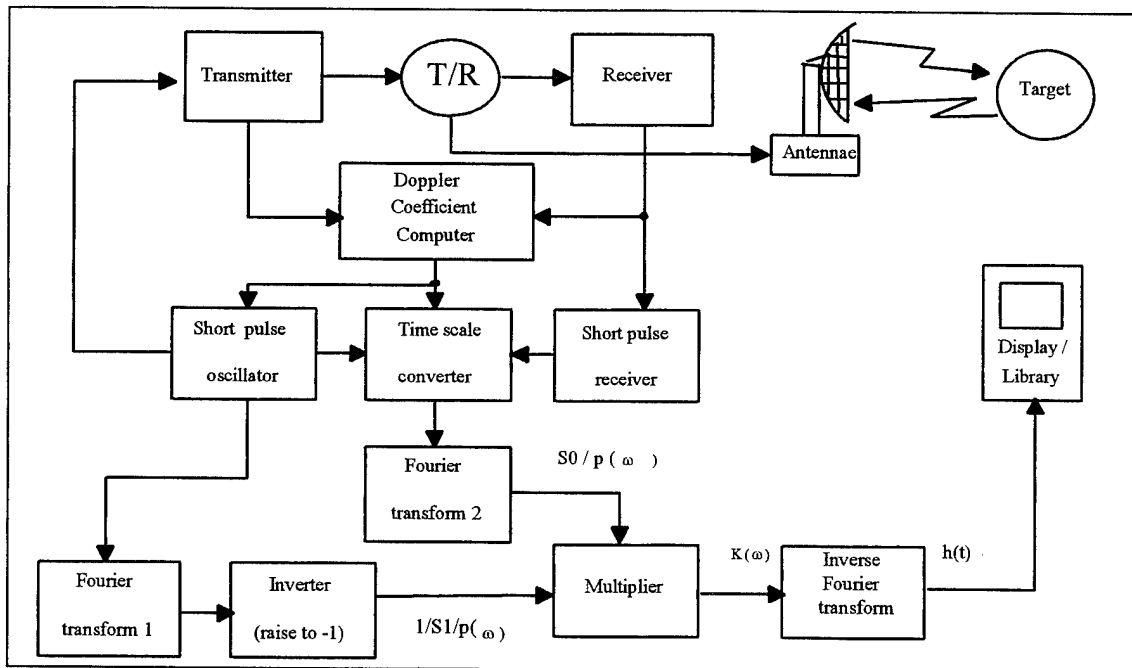


Figure 2.3. Block diagram of moving target recognition system. From V.G. Nebadin, "Methods and Techniques of Radar Recognition."

The first signal processing stage in this system consists of measuring the Doppler coefficient D. For this a long sinusoidal (CW) transmission is used. The long transmission originates in the transmitter and passes through the T/R switch to the antenna. After reflecting on a moving target, the echo arrives at the antenna, passing through the T/R switch to the receiver.

The receiver output is applied to the Doppler coefficient computation circuit. On determining this coefficient, short transmitter pulses are generated by the short pulse oscillator. Simultaneously, some of the output is fed to the time scale converter, which is designed to shape a standard series of signals with time delays corresponding to the scattering points of a moving target. This standard pulse train is Fourier transformed and inverted. Inversion implies raising this spectrum to the -1 power, so that the frequency response

$$K(\omega, \theta) = \frac{S_r(\omega, \theta)}{S_t(\omega, \theta)} \quad (2.5)$$

where $S_r(\omega, \theta)$ and $S_t(\omega, \theta)$ are the spectrum of the received echo and the transmitted pulse respectively, is obtained at the multiplier output. The product $K(\omega, \theta)$, of the received echo's spectrum and the inverted transmitter spectrum, is inverse transformed to provide output pulses, $h(t, \theta)$,

$$h(t, \theta) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} K(\omega, \theta) \exp(j\omega t) d\omega \quad (2.6)$$

representing the target's scattering points (Figure 2.4). Finally the target's signature is passed to the "evaluation" console for comparison with the existing library.

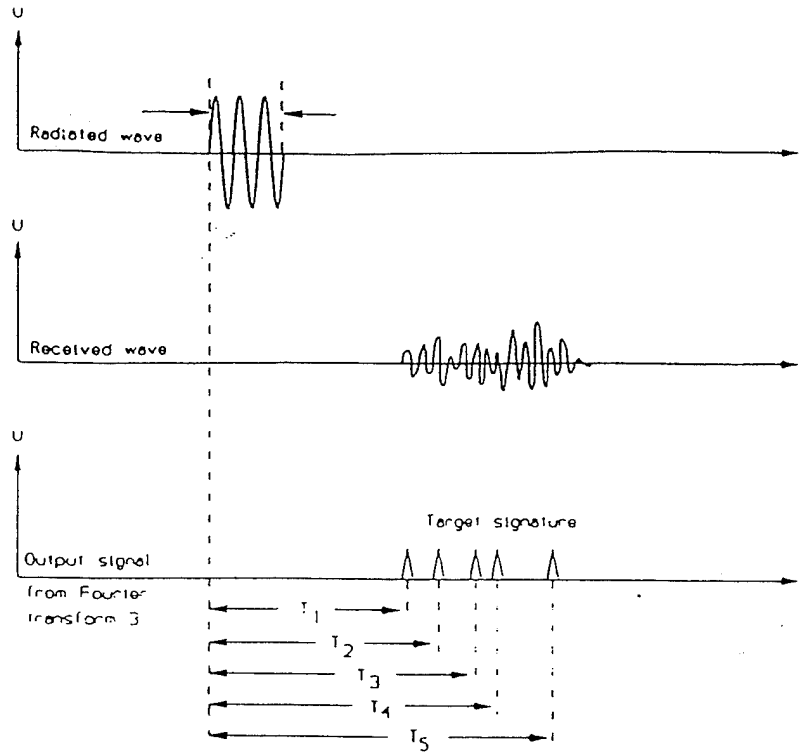


Figure 2.4. Waveforms showing principle of operation of moving target recognition system. From V. G. Nebadin, *"Methods and Techniques of Radar Recognition."*

2. Subspace Methods: An Estimation of a Signal's Discrete Components

a. Disadvantages of the Fourier Transform.

In the previous subsection we saw a method of identifying a target by the spectrum of its response to a very short pulse. In the method described the spectrum of the target is obtained by the use of Fourier transforms. The disadvantage of Fourier-based methods is that the frequency resolution of the transform depends on the number of the samples used. As stated in [3], if we consider a finite sequence of numbers $\{x_n\} = \{x_0 \ x_1 \ x_2 \ \dots x_{N-1}\}$ the Discrete Fourier Transform(DFT) of this sequence can be represented by the sequence $\{X_m\} = \{X_0 X_1 \dots X_{N-1}\}$. The two sequences are related by

$$X_m \equiv \sum_{n=0}^{N-1} x_n \exp(-i \frac{2\pi}{N} mn), m = 0, 1, 2, \dots, N-1 \quad (2.7)$$

$$x_n \equiv \frac{1}{N} \sum_{m=0}^{N-1} X_m \exp(i \frac{2\pi}{N} mn), n = 0, 1, 2, \dots, N-1 \quad (2.8)$$

It can be seen from equation (2.8) that x_n is comprised of N sine wave components. The fact that the frequencies of these sinusoids are $0, 1/N, 2/N, \dots, (N-1)/N$, shows that the DFT cannot resolve adjacent frequencies in increments finer than $1/N$, where N is the length of the time sequence $\{x_n\}$. It is also proven in [3] that appending zeros to the time sequence x_n (known as zero-padding) does not improve the DFT's resolution but simply allows a better display of the signal's spectrum. Figure 2.5 shows the DFT of a time sequence zero-padded to a length of $(K-1)N$ zeros for $K = 1, 2, 4, 16$. The time sequence consists of three sine waves and has a length of 16 samples.

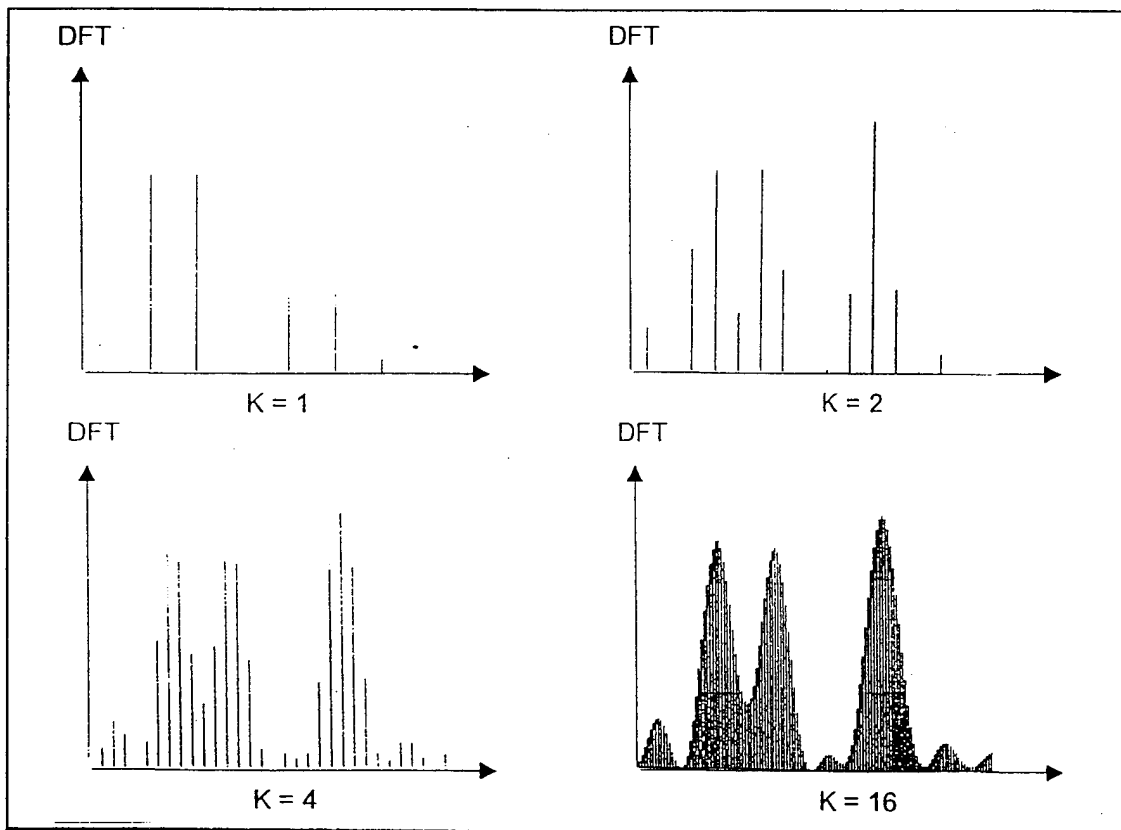


Figure 2.5. Effect of zero padding in spectral resolution $K=1, 2, 3, 4$. From W.A.Gardner, "Statistical Spectral Analysis."

It is clear from Figure 2.5 that even if the sinusoids present in a signal are resolvable by the transform it is usually necessary to "zero pad" the transformed time sequence in order to obtain an "adequate" representation of the sequence's spectrum.

It is shown in [11] that a target's echo return consists of exponentials in white noise, with the frequencies of these exponentials depending on the resonances of the target that are excited by the short radar pulses. Specifically the target echo caused by an arbitrary excitation pulse $g(t)$ will be

$$r(t, \theta) = \sum_{m=1}^M c_m \exp(s_m t) + w(t) \quad (2.9)$$

where c_m are the complex coefficients determining the strength of the natural modes in the response, s_m is the m^{th} natural resonant frequency, $w(t)$ is a noise component of zero mean and flat power spectral density over the bands of the excitation frequencies, and the variable θ expresses the dependence of the impulse response on the aspect angle.

In the subsections following, methods designed for the estimation of complex exponentials in noise are presented. The idea behind these methods is to decompose the observation vector space into a subspace associated with the signal and a subspace associated with only the noise. For this presentation we follow the discussion of subspace methods in [5].

b. Subspace Methods Principles

The motivation for these methods originated from the work of a Russian scientist, V.F. Pisarenko, which dealt with the estimation of complex exponentials in white noise [12]. Part of the work covered the case of the estimation of the spectra of time series data.

To begin, let us consider a random sequence consisting of a single complex exponential in white noise.

$$x[n] = As[n] + w[n] \quad (2.10)$$

where $s[n]$ is of the form

$$s[n] = e^{j\omega_0 n} \quad (2.11)$$

and the complex amplitude

$$A = |A|e^{j\phi} \quad (2.12)$$

is random (i.e., both $|A|$ and ϕ are random variables with ϕ uniformly distributed). The noise is assumed to be uncorrelated with the signal, and has mean zero and variance σ_0^2 . Figure 2.6 depicts the spectrum of this random sequence where $P_0 = E\{|A|^2\}$ is the variance of A .

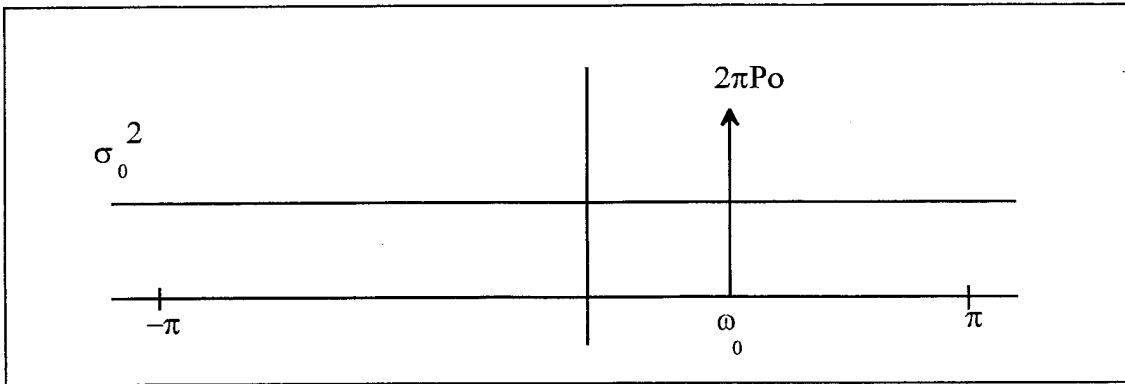


Figure 2.6. Power spectral density of a complex exponential in white noise. From C. W.

Therrien, *"Discrete Random Systems and Statistical Signal Processing."*

Consider now the vectors that compose the N samples of the sequence $x[n]$:

$$\mathbf{x} = [x[0] \ x[1] \ \dots \ x[N-1]]^T \quad (2.13)$$

$$\mathbf{w} = [w[0] \quad w[1] \quad \dots \quad w[N-1]]^T \quad (2.14)$$

$$\mathbf{s} = [1 \quad e^{j\omega_0} \quad \dots \quad e^{j(N-1)\omega_0}]^T \quad (2.15)$$

we can then write (2.10) as

$$\mathbf{x} = A\mathbf{s} + \mathbf{w} \quad (2.16)$$

Since the signal and the noise are uncorrelated, the correlation matrix of the observation vector is:

$$\mathbf{R}_x = E\{A\mathbf{s}(A\mathbf{s})^{*T}\} + E\{\mathbf{w}\mathbf{w}^{*T}\} = P_0\mathbf{s}\mathbf{s}^{*T} + \sigma_0^2\mathbf{I} \quad (2.17)$$

where \mathbf{I} is the identity matrix and

$$P_0 \equiv E\{AA^*\} = E\{|A|^2\} \quad (2.18)$$

Now if we examine \mathbf{R}_x we will observe that one of its eigenvectors is the signal vector \mathbf{s} . To see this, multiply both sides of (2.16) by \mathbf{s} and observe that $\mathbf{s}^{*T}\mathbf{s} = N$, thus

$$\mathbf{R}_x\mathbf{s} = (P_0\mathbf{s}\mathbf{s}^{*T} + \sigma_0^2\mathbf{I})\mathbf{s} = P_0\mathbf{s}\mathbf{s}^{*T}\mathbf{s} + \sigma_0^2\mathbf{s} = (NP_0 + \sigma_0^2)\mathbf{s} \quad (2.19)$$

This also shows that the eigenvalue corresponding to the eigenvector \mathbf{s} has the value of $NP_0 + \sigma_0^2$. The correlation matrix has a set of N orthonormal eigenvectors, where all $N-1$ other eigenvectors are orthogonal to \mathbf{s} . If we consider one of the $N-1$ other eigenvectors \mathbf{e}_i and use the fact that $\mathbf{s}^{*T}\mathbf{e}_i = 0$, then from Equation 2.17 we have:

$$\mathbf{R}_x\mathbf{e}_i = P_0\mathbf{s}\mathbf{s}^{*T}\mathbf{e}_i + \sigma_0^2\mathbf{e}_i = \sigma_0^2\mathbf{e}_i \quad (2.20)$$

this shows that all the remaining eigenvalues of the correlation matrix are equal to σ_0^2 .

The above derivation shows that the set of parameters $(\omega_0, P_0, \sigma_0^2)$ that define the power density spectrum of the sequence $x[n]$, can be found by solving the eigenvalue problem for \mathbf{R}_x . For the case of one sinusoid the estimation of the spectrum can be found by the following procedure:

- Form the correlation matrix.
- Compute the eigenvalues and eigenvectors of the correlation matrix.
- Locate the $N-1$ smallest eigenvalues which correspond to the noise. Their values will be approximately σ_0^2 (In theory the eigenvalues are equal to σ_0^2 . In practice, since the correlation matrix is estimated from the data, the values will be only approximately equal.).
- Locate the remaining largest eigenvalue which corresponds to the sinusoid, and has a value $NP_0 + \sigma_0^2$. Having this value and σ_0^2 we can compute P_0 (the power of the sinusoid).
- Examine the eigenvector which corresponds to the largest eigenvalue and determine its frequency ω_0 .

Consider now the general case of M independent signals in noise ($M < N$). Then $x[n]$ will be:

$$x[n] = \sum_{i=1}^M A_i s_i[n] + w[n] \quad (2.21)$$

where

$$s_i[n] = e^{j\omega_i n}, \quad A_i = |A_i| e^{j\phi_i}, \quad (2.22)$$

If the noise is white and $E\{A_i A_j^*\} = 0$ (a condition usually met in practice), the correlation matrix will be:

$$\mathbf{R}_x = \sum_{i=1}^M P_i \mathbf{s}_i \mathbf{s}_i^{*T} + \sigma_0^2 \mathbf{I} \quad (2.23)$$

where

$$P_i \equiv E\{A_i A_i^*\} = E\{|A_i|^2\}, \quad \mathbf{s}_i = [1 \ e^{j\omega_i} \ \dots \ e^{j(N-1)\omega_i}]^T \quad (2.24)$$

By following the same reasoning as in the case of one exponential in white noise, it can be shown that the correlation matrix \mathbf{R}_x , will have M eigenvectors lying in a subspace spanned by the \mathbf{s}_i . This is known as the "signal subspace." The remaining $N-M$ eigenvectors lie in the orthogonal, complementary subspace which is known as the "noise subspace." All of the $N-M$ noise subspace eigenvectors will correspond to eigenvalues $\lambda_i = \sigma_0^2$ while all of the signal subspace eigenvectors will correspond to eigenvalues $\lambda_i > \sigma_0^2$ (see Figure 2.7). In the case that the noise is not white, a similar procedure can be carried out involving a generalized eigenvalue problem (see [5]).

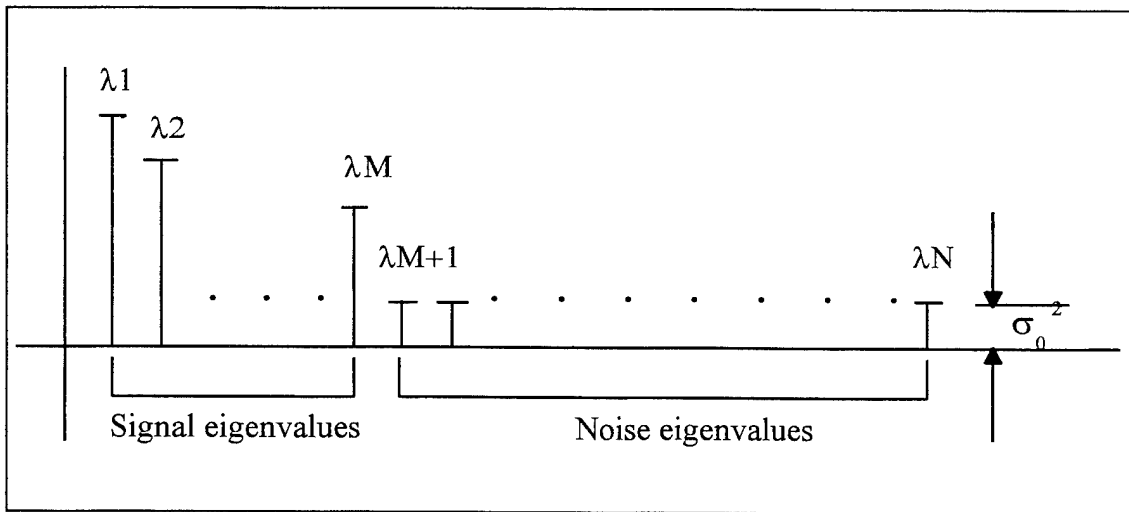


Figure 2.7. Signal and noise subspace eigenvalues for the MUSIC method. From C. W. Therrien, "Discrete Random Signals and Statistical Signal Processing."

c. Multiple Signal Classification Method (MUSIC)

In the MUSIC method, [13], the correlation matrix of order $N > M+1$ is formed and its eigenvalues and eigenvectors are found. If the number of signals is not

known it can be estimated by locating the smallest, approximately equal, set of eigenvalues. Their number will be equal to $N-M$, their value will be equal to σ_0^2 and they will correspond to the noise subspace. Once the noise eigenvalues are located, the remaining eigenvalues and eigenvectors correspond to the signal subspace¹.

The basic idea behind MUSIC is that since the signals lie in a subspace which is orthogonal to the noise subspace, this projection into the noise subspace is zero. This provides the key to estimating the frequencies of the sinusoids. Let \mathbf{w} be defined as a vector of the form

$$\mathbf{w} = [1; e^{j\omega}; \dots; e^{j(N-1)\omega}]^T \quad (2.25)$$

for an arbitrary frequency ω . Notice that when $\omega = \omega_i$ (a signal frequency), the product

$$\mathbf{w}^{*T} \mathbf{e}_i |_{\omega=\omega_i} = 0 \quad (2.26)$$

In the MUSIC method, the "pseudospectrum" $P(e^{j\omega})$ (Figure 2.8), is formed:

$$P(e^{j\omega}) = \frac{1}{\sum_{i=M+1}^N \mathbf{w}^{*T} \mathbf{e}_i \mathbf{e}_i^{*T} \mathbf{w}} \quad (2.27)$$

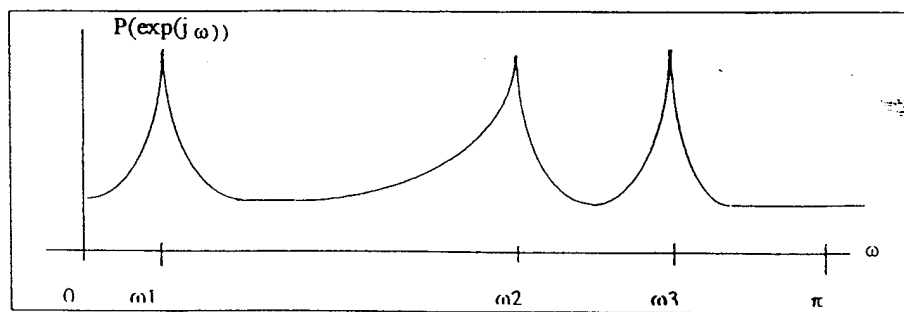


Figure 2.8. Illustration of MUSIC pseudospectrum. From C.W. Therrien, *"Discrete Random Signals and Statistical Signal Processing."*

¹ For low SNR cases the discrimination between the signal and noise eigenvalues can be done by applying certain statistical criteria such as the Akaike Information Criterion (AIC) and the Minimum Description Length (MDL). These methods are described later in this chapter.

The operation in Equation 2.27 can be interpreted as a projection of the vector \mathbf{w} onto the noise subspace. The denominator of Equation 2.27 is the squared magnitude of this projection. Notice that because of Equation 2.26 $P(e^{j\omega_i}) = \infty$, i.e., the pseudospectrum has peaks at the signal frequencies.

An alternative method using the concept of "eigenfilters," also exists for the MUSIC approach. This method which is called "root MUSIC," can be derived if we express the denominator of Equation 2.27, as follows. Let the eigenfilter $E_i(z)$ be defined as

$$E_i(z) = e_i[0] + e_i[1]z^{-1} + \dots + e_i[N-1]z^{-(N-1)} \quad (2.28)$$

where the $e_i[n]$ represent the components of the noise subspace eigenvector \mathbf{e}_i . Then the denominator of Equation 2.27 can be written as

$$\sum_{i=M+1}^N \mathbf{w}^* \mathbf{e}_i \mathbf{e}_i^* \mathbf{w} = \sum_{i=M+1}^N E_i(e^{j\omega}) E_i^*(e^{j\omega}) \quad (2.29)$$

Thus Equation 2.27 can be written as

$$P_{MUSIC}(e^{j\omega}) = \frac{1}{\sum_{i=M+1}^N E_i(z) E_i^*(1/z^*)} \quad , \quad \text{for } z = e^{j\omega} \quad (2.30)$$

Since the denominator of Equation 2.30 goes to zero at $z = e^{j\omega_i}$ ($i = 1, 2, \dots, M$), the denominator polynomial has M roots lying on the unit circle. These M roots (actually double roots) correspond to the signal frequencies. One should note that each eigenfilter is a polynomial of degree $N-1$. This means that each eigenfilter will have $N-1$ roots; M of these correspond to the frequencies ω_i , $i = 1, \dots, M$, and lie on the unit circle. The remaining $N-M-1$ so-called "spurious" roots are not on the unit circle and do not play any part in locating the spectral lines. In theory these roots do not cause any anomalies, but in practice they could be mistaken for signal components if they are very close to the unit

circle. The summing of the eigenfilter terms in the denominator of Equation 2.30 tends to move the spurious roots away from the unit circle. Thus the polynomial

$$P_{MUSIC}^{-1}(z) = \sum_{i=M+1}^N E_i(z)E_i^*(1/z^*) \quad (2.31)$$

used in MUSIC tends to behave better than the individual eigenfilters.

In the application of root MUSIC, the polynomial $P^{-1}(z)$ is formed, its roots are located, and the M roots on (or closest to) the unit circle determine the signal frequencies.

As mentioned earlier in this section, it is not easy in practice to discriminate between the noise and the signal eigenvalues, just by inspection, when the signal-to-noise ratio is low. Wax and Kailath [14] developed a formulation of the Akaike Information Criterion (AIC) and the minimum description length (MDL) that is applicable to this problem. Both of these quantities have a minimum when their argument is equal to the number of signals present. For the case of signals in noise Wax and Kailath showed that if the observation vector is Gaussian with zero mean, both AIC and MDL can be expressed as follows:

$$AIC(M) = -2K(N-M) \ln \rho(M) + 2M(2N-M) \quad (2.32)$$

$$MDL(M) = -K(N-M) \ln \rho(M) + \frac{1}{2}M(2N-M) \ln K \quad (2.33)$$

where $\rho(M)$ is the ratio of the geometric to the arithmetic mean of the eigenvalues

$$\rho(M) = \frac{(\lambda_{M+1} \lambda_{M+2} \dots \lambda_N)^{\frac{1}{N-M}}}{\frac{1}{N-M}(\lambda_{M+1} \lambda_{M+2} \dots \lambda_N)} \quad (2.34)$$

The estimated value of M , the number of signals, will be the one which minimizes the right hand side of one of the above Equations 2.32 or 2.33. Once the value of M is chosen, the noise power, can be estimated from

$$\hat{\sigma}_0^2 = \frac{1}{N-M}(\lambda_{M+1} + \lambda_{M+2} + \dots + \lambda_N) \quad (2.35)$$

C. METHODS OF RECOGNITION USING NARROWBAND SIGNALS

The addition of a very short pulse to the existing pulse "menu" can betray the intention and identify the radar as being from a warship of advanced capabilities, rather than from an innocent merchant ship. This fact forces us to try to achieve a level of target classification using the standard waveforms of the radar. In [7] a set of features of the video signals of the target is used in order to classify marine targets. These features are the following:

- The symmetry of the waveform;
- The spread of the waveform;
- The effective width of the waveform;
- The bounce (jitter) of the waveform envelope;
- The increase or decrease of the envelope with time;
- The shape of the waveform;
- Generalized measures of recorded waveform parameters;

The features used by the authors of [7] in order to classify their targets into categories were called the "frequency of occurrence of specific binary words" and the "shape of radar returns." Each of these approaches used a series of transformations of the digitized target echo. The procedure to conduct the above approaches as they appear in [7] are:

1. Frequency of Occurrence of Specific Binary Words

The target's echo, which is a time sequence, is Fourier transformed in order to obtain a sequence, which would not be a function of the time delay between the transmitted signal and the echo. This new series is now Mellin transformed, in order to obtain a series of data which are not a function of the target's aspect angle relative to the classifying radar. Finally the transformed data are converted to binary sequences. Guirong, Wei and Wenxian [7] found that some classes of ships are characterized by specific binary words.

2. Shape of the Radar Returns

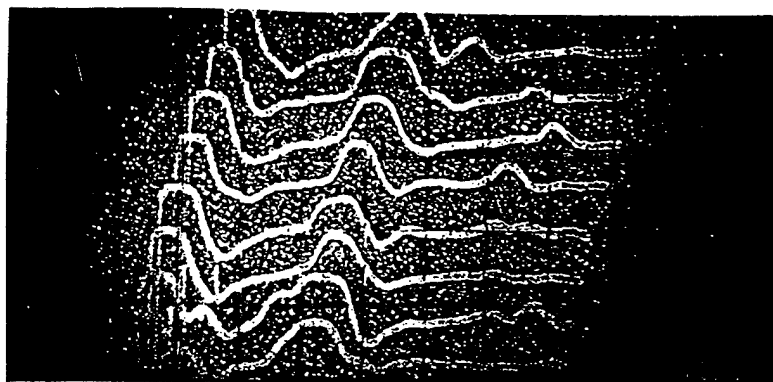
To extract this feature the target's echo is filtered through a transform defined in [7] as λ - cut transform. If we consider a sequence $X = [x_1 \ x_2 \ \dots \ x_N]$ then

$$\mu(x_j) = \frac{x_j}{\max(X)}, j = 1, 2, \dots, N \quad (2.35)$$

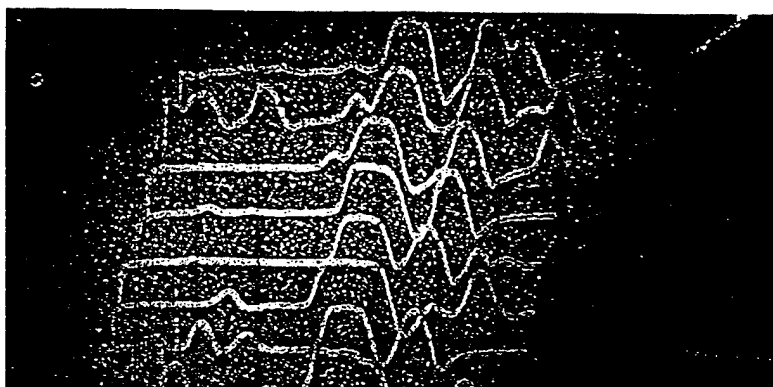
$$A_\lambda = \{\mu(x) \geq \lambda, \lambda \in [0, 1]\} \quad (2.36)$$

when we use m levels, $\lambda_1 \dots \lambda_m$ we obtain a sequence of m cuts. The sequence A_λ is the λ - cut transform of X . The next step is the "Difference transform" which is nothing else but the difference between two adjacent elements of A_λ . Finally in order to make the transformations more stable, the returns of a number of pulses are processed and then averaged.

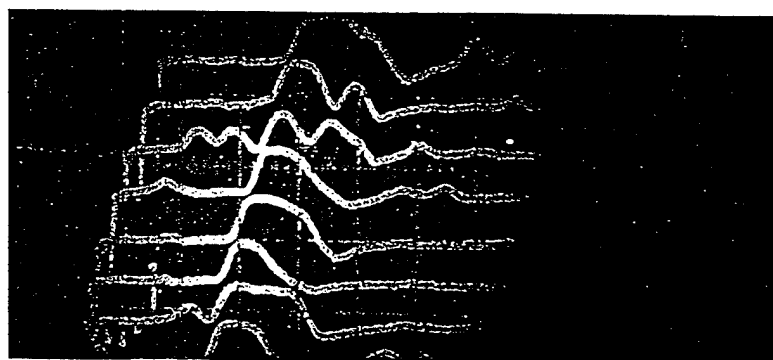
According to [7] it is possible to classify marine targets in eight types of platforms by the use of some of the above features. The probability of recognition for these eight types of ships is greater than 90% (see [2]). Figure 2.9 shows photographs of the reflected pulse trains for three types of recognized objects as shown in [2].



(a)



(b)



(c)

Figure 2.9 (a), (b), (c). Oscilloscope traces for ship of the first, second, and third type respectively. From Guo, G., W. Zhang, and W. Yi, "*An Intelligence Recognition Method for Ship Targets.*"

III. TRANSMITTER - RECEIVER MODIFICATIONS

A. TRANSMITTER REQUIREMENTS

As discussed in Chapter 1, there are two techniques for target classification or identification that could be applied with the DECCA 1226:

- Target classification by the use of narrowband signals (low resolution pulse).
- Target identification/classification by the use of broadband signals (high resolution - short pulse case).

Without any modification the radar offers a longest pulse of 1μs for ranges up to 48 nautical miles and a shortest pulse of 50 ns for ranges from 0.25 to 1.5 nautical miles. Given the two methods mentioned above we could use the long pulse for target classification and the short pulse for target recognition. In this case we should modify the radar's magnetron and timing circuits in order to provide sufficient power and time for the short (50 ns) pulse to travel the largest possible distance and return. Still this modification would provide a range resolution of 8 meters. Since the target's return is considered as the impulse response of a group of individual scatterers, a 50 ns pulse would allow us to discriminate individual scatterers if they are more than 8 meters apart. Unfortunately this is not always the amount of detail we would like to extract from the target's return. The 8 meter resolution would be sufficient for large ships, (e.g., frigates, cruisers, destroyers large tankers or cargo ships) but would be inadequate for discriminating and identifying among corvettes, fast patrol boats, luxury yachts, small fishing vessels, etc. The necessity to obtain a clear tactical picture dictates a further modification of the radar in order to provide the shortest possible pulse with the maximum available power.

From the radar equation [8]

$$R_{\max}^4 = \frac{P_t \tau G A \rho_a \sigma n E_i(n)}{(4\pi)^2 k T_s (E / N_0)_1 L_s} \quad (3.1)$$

where

- R_{\max} is the maximum radar range
- P_t is the transmitted peak power
- τ is the pulse duration
- G is the antenna gain
- ρ_a is the antenna efficiency
- σ is the target's radar cross section
- n is the number of hits integrated
- $E_i(n)$ is the integration efficiency
- L_s is the systems losses
- k is Boltzman's constant, $k = 1.38 / 10^{23}$ J/deg
- T_s is the system's noise temperature
- E / N_0 is the signal to noise energy ratio

we can see that the maximum detection range is proportional to the product $P_t \tau = E_t$, where E_t is the energy in the transmitted pulse. If we do not change any of the other parameters of the radar, then to preserve the same detection ranges for the same range scales, we should keep the energy in the transmitted pulse constant. Thus, if we wish to achieve a range resolution of 1 m we should use short pulses (according to Chapter II Section 2c) of 6.7 nsec. That would mean that in order to detect targets at the same range as with the regular pulse, we should increase the transmitted power by a factor of the pulse duration divided by 6.7 ns. Table 3.1 shows the increase in power that should be provided to the radar in each range scale in order to identify targets with an 8 meter and a 1 meter resolution. For this presentation the data of Table 2.2 was used.

RANGE SCALE	PULSE LENGTH (ns)		Power Multiplication 1 meter resolution		Power Multiplication 2 meters resolution	
	Short	Long	Short	Long	Short	Long
0.25	50	50	7.25	7.25	1	1
0.5	50	250	7.25	36.23	1	5
0.75	50	250	7.25	36.23	1	5
1.5	50	250	7.25	36.23	1	5
3	250	1,000	36.23	144.92	5	20
6	250	1,000	36.23	144.92	5	20
12	250	1,000	36.23	144.92	5	20
24	1,000	1,000	144.92	144.92	20	20
48	1,000	1,000	144.92	144.92	20	20

Table 3.1. Necessary transmitted power multiplication for target identification with 1 meter and 8 meter resolution in the various range scales.

Since the maximum power of the DECCA 1226 is nominally 25 KW, we can use the calculations of Table 3.1 to obtain the required power for target identification for each range scale. This is given in Table 3.2.

RANGE SCALE N. MILES	POWER FOR $\Delta R = 1M$ (KW)		POWER FOR $\Delta R = 8 M$ (KW)	
	SHORT PULSE	LONG PULSE	SHORT PULSE	LONG PULSE
6	905.75	3,623	125	500
12	905.75	3,623	125	500
24	3,623	3,623	500	500
48	3,623	3,623	500	500

Table 3.2. Required power for target identification.

It is obvious from the data of Table 3.2 that by just modifying the transmitter we cannot hope for serious target identification at long ranges. Besides increasing the transmitted power we may be able to increase the sensitivity of the receiver, thus increasing the maximum target identification distance.

According to [9] magnetron radars have been used for target identification for ranges of several miles with pulse lengths on the order of 10 ns. A next step after this thesis would be to search the commercial market for packages of upgrades involving the transmitter's power and shortest pulse.

B. RECEIVER MODIFICATION

After deciding on the desired combination of range resolution and transmitted power, the receiver unit needs to be modified to handle the new power and bandwidth. Furthermore since the receiver's sensitivity plays a decisive role in the maximum distance of detection, specific packages of sensitivity upgrades should also be sought in the commercial market. The fact that the radar was last improved in 1975 leads us to the assumption that by applying modern technology (more powerful and sophisticated magnetrons and more sensitive receivers) we will be able to extract identification information from target returns at a useful range. As described in Chapter 2 Section C, target classification can be achieved with the use of narrowband (long duration) pulses. Our receiver should therefore be able to provide target classification at long ranges, using feature extraction algorithms, and target identification as the target's range decreases relative to our platform. To make target data available to our processing unit (PC or workstation) we would need to digitize and then feed the data to the processor through an interface. As in the case of the authors of [7] we will channel the data from the output of the video detector to the processing unit. An example of such data channeling for testing purposes is also given in the information manual of the HP 5185T digitizing oscilloscope. This specific oscilloscope has the capability to sample and store radar waveforms of up to 125 Mhz (the DECCA 1226 has an IF of 60 Mhz) and to execute FFT computations in order to provide the returned pulse's digital spectrum. The

digitizing interface and processing units can be connected in parallel with the radar's video display units in order not to interfere with DECCA's primary purpose which is navigation. A block diagram of the radar after the addition of the target classification/identification devices is given in Figure 3.1.

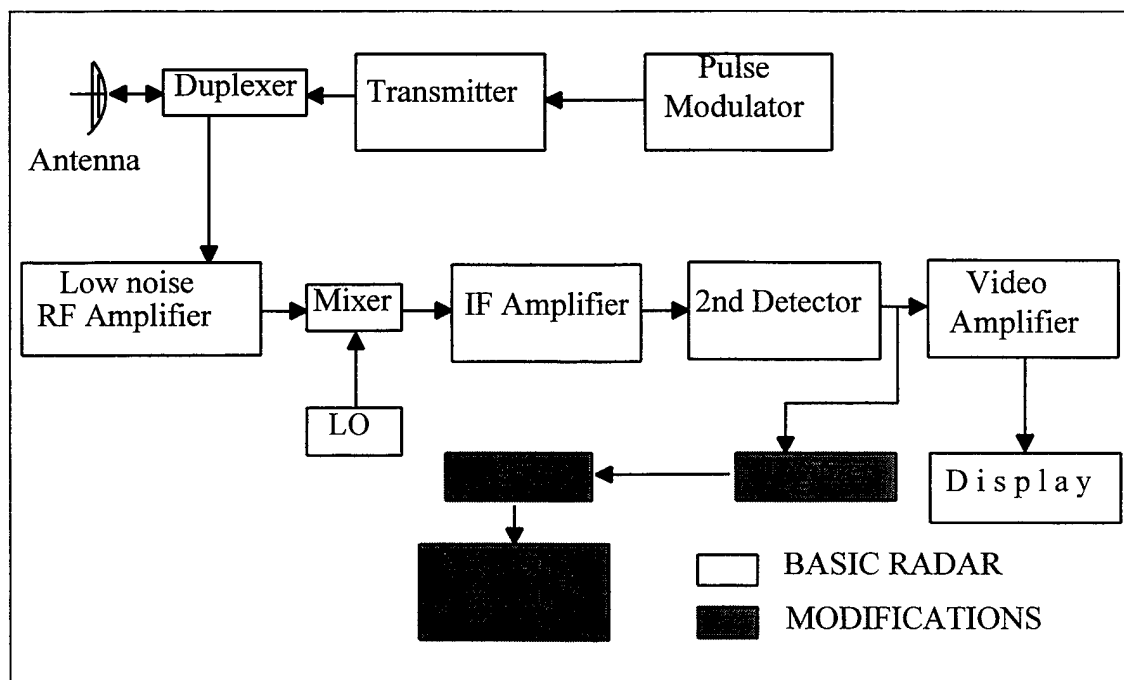


Figure 3.1. Block diagram of the Radar with the addition of a signal processing unit.

C. IDENTIFICATION / CLASSIFICATION PROCESS

The processing unit now has available the target's echo in order to analyze, classify and finally identify it. These steps will be executed in two phases: the classification phase, which starts when the target will be initially detected at a greater range; and the identification phase, which takes place at a distance that is determined by the transmitter's upgraded performance.

1. Classification Phase

In this phase the target's echo is processed as described in Chapter 2, Section D, and the target is assigned a specific class. The classification process is shown in Figure

3.2 below.

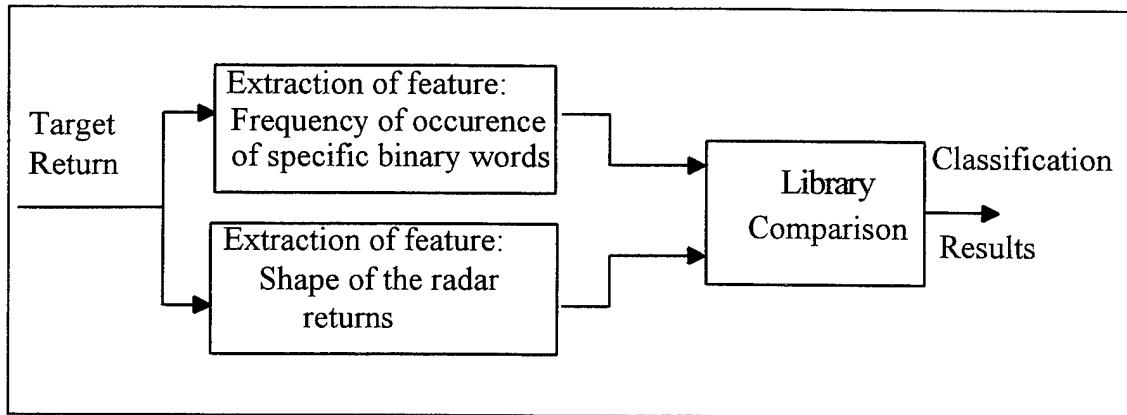


Figure 3.2. Target classification phase for the modified DECCA 1226.

1. Feature "Frequency of Occurrence of Specific Binary Words".

In order to extract the above feature we will have to "pass" the radar's echo through a series of transformations:

- Fourier transform.
- Mellin transform
- Coding transformation, where the final features are selected.

2. Feature "shape of the radar returns".

For this feature the target's echo has now to be filtered through the following:

- λ – cut transform
- Difference transform
- Averaging of a number of transformed echo returns

The transforms and feature extraction patterns are described in Chapter 2 Section C. The classification results, a positive or negative match with the existing library, could be fed to a tactical tracking system or just announced to personnel or officers onboard.

2. Identification Phase

Once the target is in range allowing for short-pulse illumination the MUSIC method will be applied in order to extract the target's frequency response from the returned echo. The various steps to extract the target's frequency response are:

- Formulation of the target return correlation matrix (time domain data).
- Eigenvalue-eigenvector decomposition of the correlation matrix.
- Identification of the sinusoidal eigenvalues and the noise standard deviation, either by inspection or the AIC/MDL criteria.
- Formulation of the eigenfilter and the sinusoidal frequencies by estimating roots.
- Estimation of the power content at each of the signal's frequencies.

After the target's frequency response is extracted, the set of M resonant frequencies and their powers are stored in a matrix of size 2 by M . This matrix will then be fed to the identification library where they will be either matched or added to the library. The various phases of the target identification process can be seen in Figure 3.3 below.

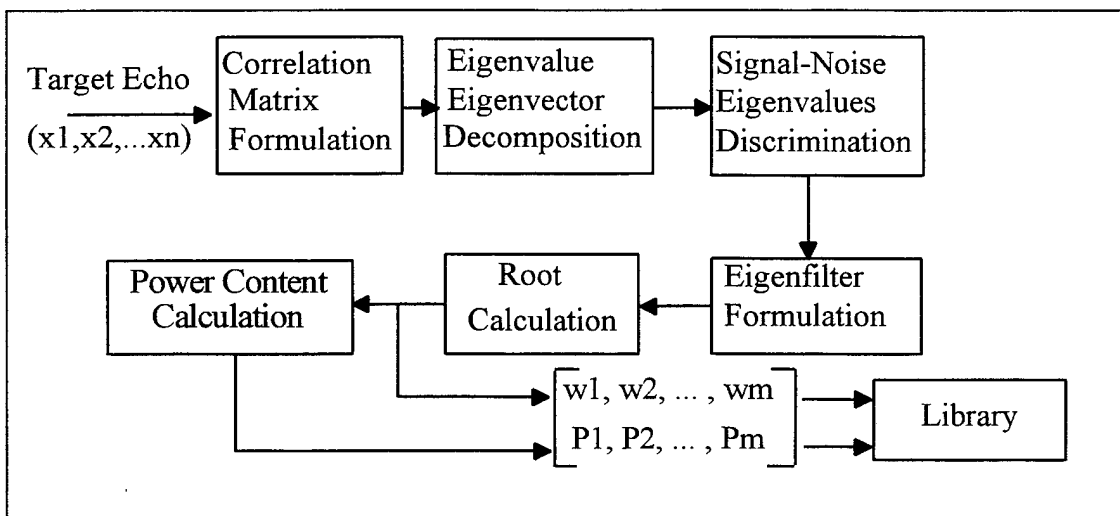


Figure 3.3. Target identification process.

Some limited simulations of the targets were performed using a very small sample of unclassified data but due to the extremely limited size of the data sets the results were inconclusive. It is recommended that further tests be performed on the large classified data set as follow-on research by a student with the necessary clearance level.

IV. SUMMARY - CONCLUSIONS

The idea behind this thesis was to determine the possibility of adding features for target classification and identification to an older generation radar like the DECCA 1226 in order to be able to conduct covert naval operations. Such a modification would be possible by taking advantage of the increased capabilities of personal computers and workstations that made possible the practical implementation of signal processing techniques restricted in the past only by computational barriers.

There are many techniques available for target classification and identification (from the unclassified literature) but the restriction that the modifications should not affect the radar's "commercial signature" limits what can be accomplished. In particular only classification can be achieved with the DECCA's ordinary long pulse while both classification and identification can be done with the very short pulses. The method selected for classification was an algorithm developed by a group of Chinese scientists for use in low resolution radars. The Chinese scientists manage to classify targets into six different groups.

In the case of target identification there are two options. Either use the radar's shortest pulse but compromise resolution, or modify the transmitter in order to provide a shorter pulse and compromise the anonymity of the platform which carries the radar. In any case the target's identity is extracted by determining the target's echo spectrum, which is the target's frequency response. The method selected for the extraction of the spectrum is called MUSIC; it was preferred over the Fourier transform because it overcomes the limitations in frequency resolution of the Fourier transform.

The actual performance of the identification subsystem will depend on the available power and shortest pulse length that can be provided by the contractors that are selected to modify the radar. This is one area which is left unexamined in this thesis. The connection of the radar with a PC or similar computer has already been done for target classification in [10].

The computer simulation was restricted to the implementation of the MUSIC method to an unclassified version of target data from past research. In order to evaluate the radar's classification and identification capabilities one would need to simulate the transmission modes over a variety of targets and run the simulated target returns through the described algorithms. In case of positive results then a laboratory simulation with model targets should be set up for further evaluation until the actual radar is developed and tested.

From the theoretical point of view there is no reason to doubt the ability to classify and even identify naval targets with the modified DECCA 1226. The idea of the modified civilian radar could be better implemented in commercial radars which use frequency modulated pulses and thus do not face the problem of power availability and restrictions in the shortest available pulse.

As a next step for further research the classification algorithms should be tested on real data sets, and the ability to discriminate between different targets should be evaluated using the features derived from the target modeling. Since the data sets of interest are classified, this work will need to be performed by a student that has proper clearance.

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